A COMPARATIVE EXPERIMENTAL STUDY OF CAPACITOR DIELECTRICS UNDER RINGING CONDITIONS

T.F. Podlesak, K. Fonda
Army Research Laboratory
Pulse Power Components Branch ATTN: AMSRL-EP-MC
Fort Monmouth, NJ 07703-5601

J. Creedon
Consultant
Little Silver, NJ

R. Ulrich
Vitronics
15 Meridian Road
Eatontown, NJ 07724

Abstract

Five different types of pulse power capacitors, each with a different dielectric material, were evaluated in an underdamped circuit. The purpose of these measurements was to determine the applicability of the various capacitor technologies for use in circuits where severe ringing will be required. Such circuits could include induction type electromagnetic launchers. It was found that severe losses, due to the effective series resistance (ESR) of the capacitors, manifested themselves. This places severe restrictions on the application of such components to circuits that require highly efficient transfer of energy from energy storage to the load. The degree of the loss varies considerably from capacitor dielectric to dielectric and from electrode construction to electrode construction.

Introduction

The U.S. Army Pulse Power Center at Fort Monmouth, NJ, has been performing component evaluation on behalf of Polytechnic University, NY, for a research program that they are conducting on inductive type electromagnetic launchers. The work is being sponsored by the Army's Space and Strategic Defense Command. The launcher is termed the Linear Induction Launcher (LIL) and has been reported on in prior literature [1-2]. This system, in brief, generates, by means of ringing RLC circuits, a series of damped sine waves at different points along the launcher. A tubular armature receives energy, inductively, and "rides the wave" down the launcher. As it moves down the launcher, it acquires desired launch velocity.

The need to apply energy and accelerate the armature necessitates the efficient coupling of energy from energy storage capacitors to the armature. First experiments focused on the application of the accelerating pulses to the launcher and to the armature at the proper time intervals. In other words, this was at first a switch problem, with concern for the amount of losses incumbent in the switches, which would more than likely be ignitrons and spark gaps, given the voltages and duty these switches would most likely see.

However, it soon became apparent that the more critical factor was the equivalent series resistance (ESR) of the energy storage capacitors. Higher than expected values of ESR caused us to devise new ways of extracting energy efficiently from the energy storage elements. The Pulse Power Center has, over the years, amassed a considerable collection of various types of energy storage capacitors, with various types of dielectrics and electrode constructions. It was determined that, before we would go on with further tests for the inductive launcher components, we perform a side by side comparison of various types of capacitors under the underdamped, ringing conditions that would be necessary for the proper operation of the launcher.

Experimental Devices and Apparatus

The capacitors tested have their construction and properties listed in Table 1. The test apparatus is shown schematically Figure 1 and photographically in Figure 2.

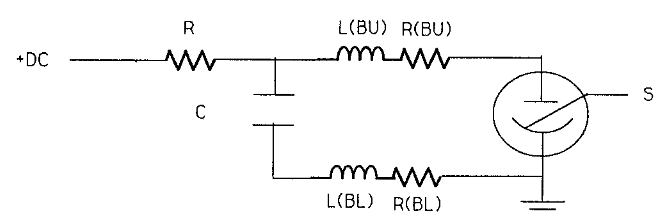

Figure 1. Schematic of capacitor test apparatus, where L(BU) and L(BL) are upper and lower buswork inductance, respectively, and R(BU) and R(BL) are upper and lower buswork resistance, respectively. R is a charging resistor.

Testing was quite straightforward. A capacitor under test was charged to 500 V and then discharged into a short circuit through a switch. The switch was a Richardson NL 8900 ignitron, similar to switches envisioned for the launcher. The only inductance and resistance in the circuit are due to the buswork.

The results of the ring down test are shown in Figures 3-13. In all but two cases, identical capacitors are operated in series or parallel, in order to simplify measurements. Determining the frequency of the waveform and knowing the capacitance allows the dissipation resistance (RESR) to be calculated by the equation:

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.			
1. REPORT DATE **JUN 1993**	2. REPORT TYPE **N/A**		3. DATES COVERED **-**
4. TITLE AND SUBTITLE **A Comparative Experimental Stijdy Of Capacitor Dieleclrics Under Ringing Conditions**			5a. CONTRACT NUMBER
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)			5d. PROJECT NUMBER
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Army Research Laboratory Pulse Power Components Branch ATTN: AMSRL-EP-MC Fort Monmouth, NJ 07703-5601**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**			
13. SUPPLEMENTARY NOTES **See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.**			
14. ABSTRACT **Five different types of pulse power capacitors, each with a different dielectric material, were evaluated in an underdamped circuit. The purpose of these measurements was to determine the applicability of the various capacitor technologies for use in circuits where severe ringing will be required. Such circuits could include induction type electromagnetic launchers. It was found that severe losses, due to the effective series resistance (ESR) of the capacitors, manifested themselves. This places severe restrictions on the application of such components to circuits that require highly efficient transfer of energy from energy storage to the load. The degree of the loss varies considerably from capacitor dielectric to dielectric and from electrode construction to electrode construction.**			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

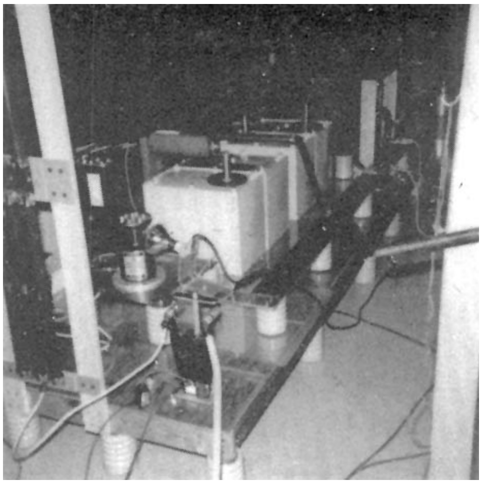

Figure 2. Photograph of capacitor test apparatus with sample capacitors installed. Ignitron switch is at left.

TABLE 1
Characteristics of Capacitors Tested

Capacitor	Capacitance	Voltage	Constuction
A	0.05 µF	15 kV	Paper/Polypropylene/ Extended Foil
B	0.05 µF	40 kV	Polypropylene/ Extended Foil
C	1.9 µF	40 kV	Paper/Polyester/Tab Foil
D	0.9 µF	40 kV	Paper/Polyester/Tab Foil
E	50 µF	44 kV	Paper/Extended Foil
F	175 µF	22 kV	Paper/Polyester/ Metallized Extended
G	342 µF	16 kV	Polypropylene/ Metallized Extended
H	900 µF	16 kV	Polyvinylidene Fluoride/Metallized Extended

$$RESR = \sqrt{\frac{4L}{C} - 4L^2\omega^2} - R(B) - R(S) \quad \text{, where} \qquad (1)$$

$\omega = 2\pi f$ f = frequency of sine wave
L = circuit inductance = 1.85 µH
C = capacitance of device (s) under test
R(B) = bus resistance - 2.319 mohms
R(S) = switch resistance = 360 µohms

and percent dissipation (%DF) calculated by the equation:

$$\%DF = 100\, \omega\, C\, RESR \qquad (2)$$

Note that equation 2 reflects the frequency dependence of the ESR.

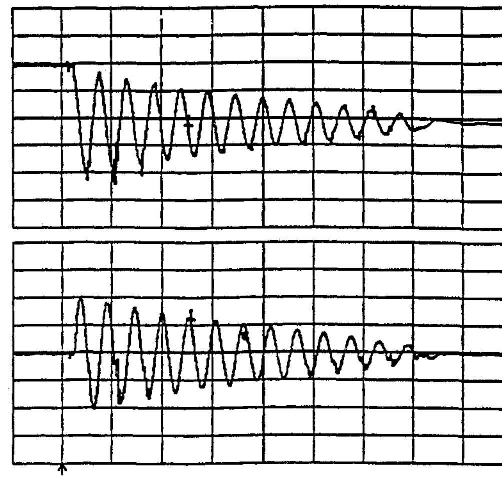

Figure 3. Two type A capacitors in parallel. Upper trace: Voltage 200 V/div. Lower Trace: Current 500 A/div. Horizontal Axis: 5µs/div.

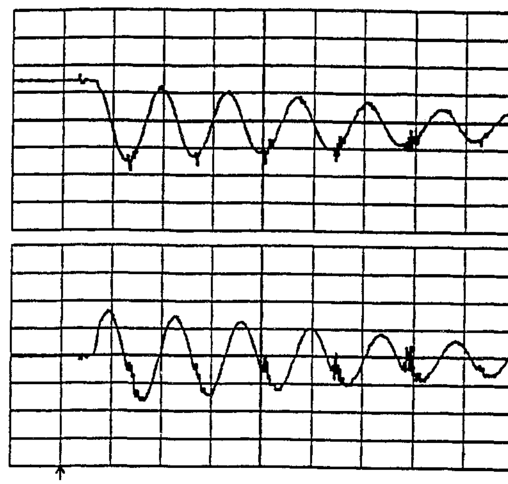

Figure 4 Two type B capacitors in parallel. Upper trace: Voltage 400 V/div. Lower tract: Current 500 A/div. Horizontal Axis: 2 µs/div.

Figure 5. Two type C capacitors in parallel. Upper trace: Voltage 200 V/div. Lower trace: Current 200 A/div. Hori zontal axis: 10 µs/div.

Figure 6 Two type C capacitors in series. Upper trace: Voltage 200 V/div. Lower trace: Current 100 A/div. Horizontal axis: 5 μs/div.

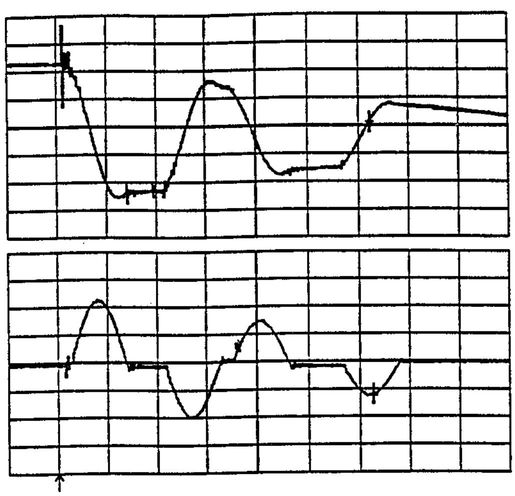

Figure 7. Two type D capacitors in parallel. Upper trace: Voltage 200 V/div. Lower trace: Current 200 A/div. Horizontal Axis: 5 μs/div.

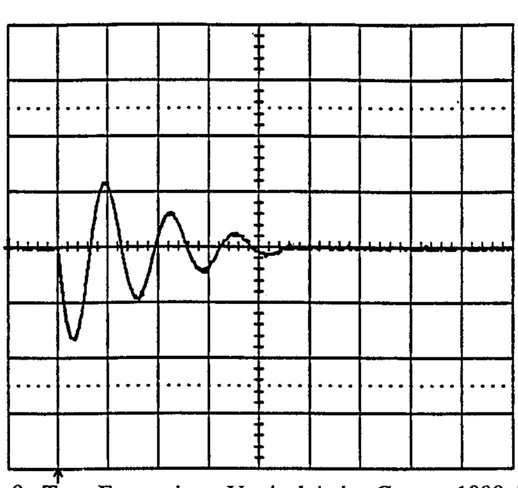

Figure 8. Type E capacitor. Vertical Axis: Current 1000 A/div. Horizontal axis: 50 μs/div.

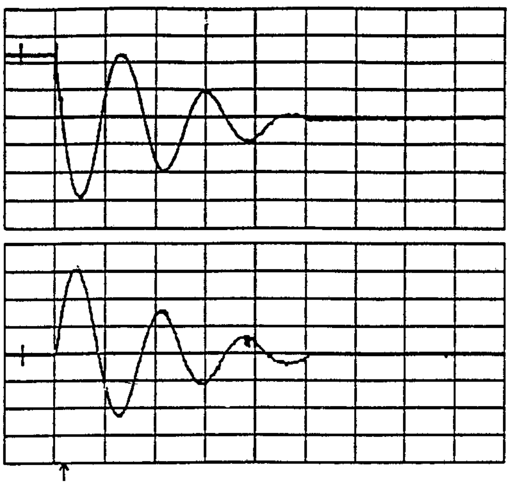

Figure 9. Two type F capacitors in Parallel. Upper trace: Voltage 200 V/div. Lower trace: Current 2000 A/div. Horizontal Axis: 100 μs/div.

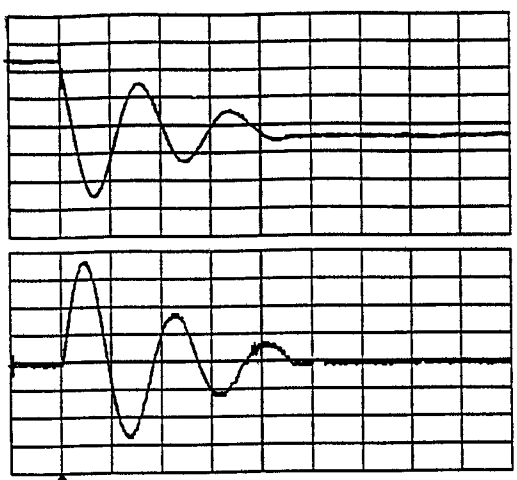

Figure 10. Two type F capacitors in series. Upper trace: Voltage 200 V/div. Lower trace: Current 800 A/div. Horizontal axis: 50 μs/div.

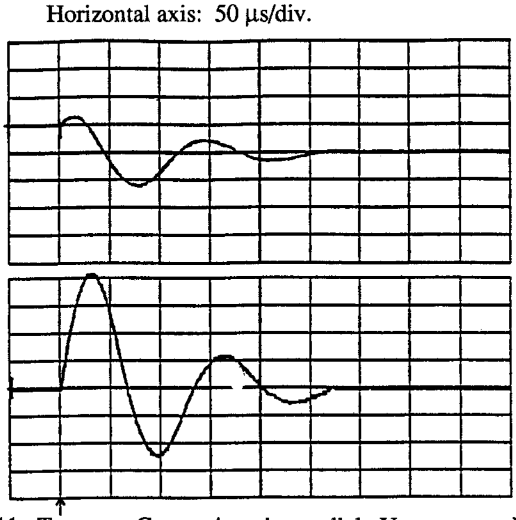

Figure 11. Two type G capacitors in parallel. Upper trace: Voltage 500 V/div. Lower trace: Current 2000 A/div. Horizontal axis: 100 μs/div.

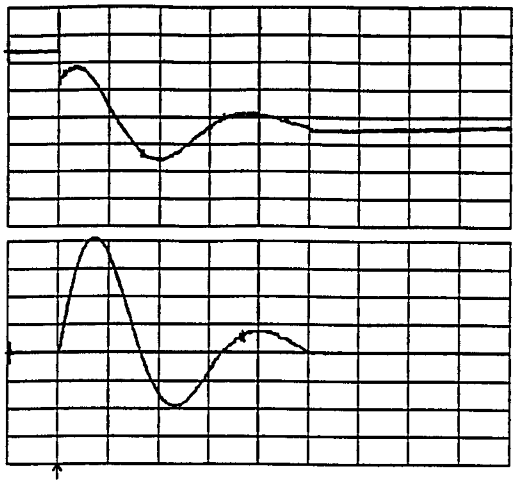

Figure 12. Two type G capacitors in series. Upper trace: Voltage 200 V/div. Lower trace: Current 800 A/div. Horizontal axis: 50 μs/div.

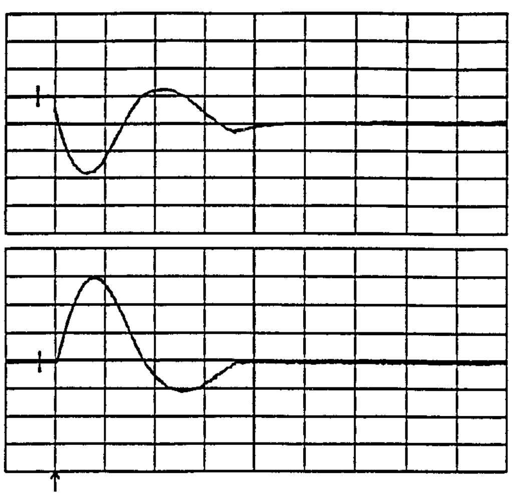

Figure 13. Type H. capacitor. Upper trace: Voltage 500 V/div. Lower Trace: Current 2000 V/div. Horizontal axis: 100 μs/div.

The results of the tests are shown in Table 2. It may be seen that the best results, i.e. the lowest percent dissipation, are obtained from paper/polypropylene/extended foil capacitors and polypropylene/extended foil capacitors. This not surprising, in that the low dissipation factor of polypropylene is well know. Of interest is to compare the dissipation factor of polypropylene/extended foil capacitors with polypropylene/ metallized extended capacitors, the latter having a dissipation factor an order of magnitude higher. In examining the data in Table 2 by capacitor type, it may be seen that, for the purposes of a ringing discharge requirement, the older designs have an advantage over the newer types.

TABLE 2

Summary of Test Results

Capacitor	Data on Figure:	RESR	Frequency	%DF
A	3	284 mΩ	385 kHz	3.4
B	4	312 mΩ	380 kHz	3.7
C	5	141 mΩ	60 kHz	10
C	6	82 mΩ	110 kHz	5
D	7	270 mΩ	90 kHz	14
E	8	35 mΩ	16 kHz	18
F	9	28 mΩ	6 kHz	18
F	10	16 mΩ	11 kHz	10
G	11	46 mΩ	3.7 kHz	37
G	12	40 mΩ	6 kHz	26
H	13	9 mΩ	3 kHz	14

Also of interest is the comparison between Figures 5 and 6, and 11 and 12. Here, measurements are made for the same capacitor at different frequencies. Note that the dissipation factor decreases at increasing frequency, a phenomenon that is well known but difficult to quantify [3-4]. There may be an advantage to this if the capacitor is used in a latter section of the launcher, where the faster flight time necessitates a higher frequency of the accelerating current.

It should be noted that the capacitors tested had been previously used, so some deterioration due to aging and use had taken place. Also, no effort was made to use a capacitor optimized to application to a particular launcher or stage of a launcher. Nevertheless, we believe these experimental tests are significant in determining the type of capacitor best suited for use in a ringing circuit for an inductive launcher of this type.

Conclusion

Based on a comparison of experimental data of various types of capacitors in side by side testing, we conclude that capacitors with polypropylene dielectrics and extended foil electrodes are the prime candidated for use in a linear induction launcher modulator circuit, operating under a ringing condition.

REFERENCES

1. T. Podlesak et.al., "Development of a High Power Modulator for a Linear Induction Launcher (LIL),' in Conference Record of the 1992 Twentieth Power Modulator Symposium, 1992, pp. 49-52.

2. J. L. He, Z. Zabar, E. Levi and L. Birenbaum, "Transient Performance of Linear Induction Launchers Fed by Generators and by Capacitor Banks," IEEE Transactions on Magnetics, vol. 27, pp. 585-590, January 1991.

3. N. C. Jaintly, A. Ramrus and B. Strickland, "High Voltage Pulsed Performance of Advanced Dielectric Materials," in Proceedings of the 18th 1988 Power Modulator Symposium, June 1988, pp. 383-380.

4. R. D. Parker, "High Power Capacitor Technology," in Proceedings of the 14th Power Modulator Symposium, June 1980, pp. 137-143.